

Imaging spin-polarized electron transport in semiconductors

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The ability to control and measure the spin of an electron in semiconductors has been proposed as the operating principle for a new generation of spin-electronic, or “spintronic” devices¹. By taking advantage of the electron’s spin degrees of freedom, today’s charged-based microelectronics may realize significant improvements in operating speed and power consumption. Many designs for functional spintronic devices have been recently proposed; for example, the “spin transistor”—a device in which ‘on’ and ‘off’ states depend on whether the current-carrying electrons are polarized spin-up or spin-down. Proposed schemes for spintronic devices generally require three essential elements: (i) a mechanism for *electrically injecting* spin-polarized electrons into semiconductors, (ii) a practical means for *spin manipulation* and transport, and (iii) an electronic scheme for *detecting* the resulting spin polarization.

Results of experimental techniques

At the National High Magnetic Field Laboratory, we have recently developed experimental tools to directly image the spin polarization of free electrons in semiconductors such as gallium arsenide (GaAs). These methods are based on scanning Kerr-rotation microscopy, wherein electron spin polarization is spatially mapped via the polarization (Kerr) rotation imparted on a linearly-polarized probe laser that is reflected from the semiconductor surface. This laser is raster-scanned to construct a two-dimensional image of electron spin polarization. Our initial studies concentrated on imaging the drift, diffusion, and flow of spin polarized electrons that were optically injected by a separate circularly-polarized laser. Spin flows were imaged in the presence of applied electric and magnetic fields, and also in the presence of applied stress to the GaAs substrate². Applied separately or in combination, these fields were used to effectively manipulate the lateral transport of electron spins in semiconductors.

The transport of spin-polarized electrons in semiconductors was modeled by theoreticians Marina Hruska and Simon Kos (T-11). In this work³, a set of generalized spin drift-diffusion equations was derived, which accurately describe the observed flow of spins in the presence of electric, magnetic, and—importantly—strain fields. Figure 1 shows the characteristic good

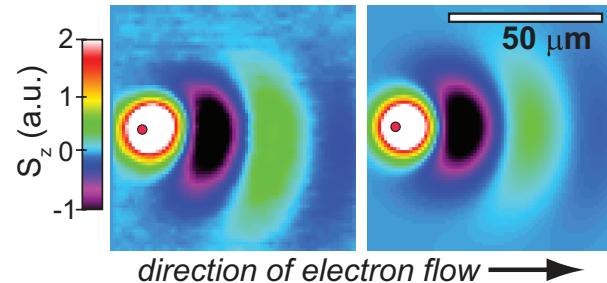


Figure 1. A comparison of actual data (left), and the results of a model (right) that is based on the spin drift-diffusion equations. Spin polarized electrons, optically injected into GaAs (red dot), subsequently diffuse and drift to the right under the influence of a small lateral electric field (10V/cm). Spin precession is caused by the application of a uniaxial stress to the GaAs sample.

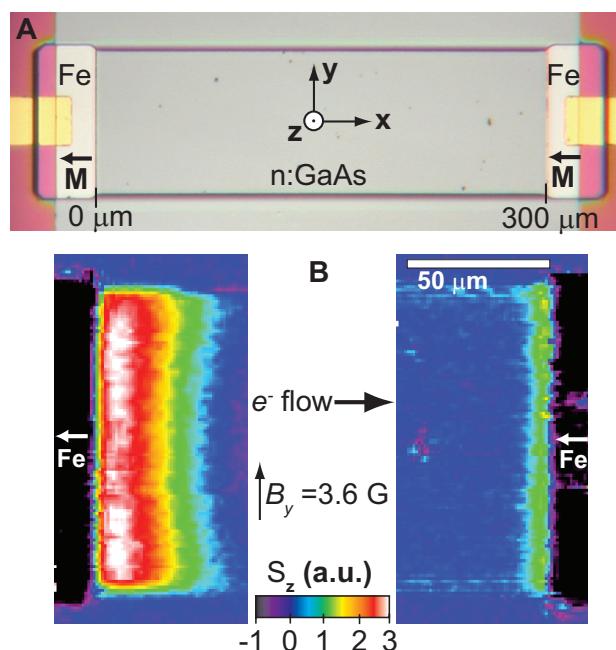


Figure 2. A) Photograph of a lateral ferromagnet-semiconductor spin transport device. The Fe/GaAs tunnel-barrier source and drain contacts are magnetized along $\rightarrow x$ as shown. The GaAs channel is 300 μm long. B) Two-dimensional images of electron spin polarization near the source and drain contacts. Efficient electrical spin injection from the source contact is clearly observed. The spin polarized electrons that accumulate near the drain contact are actually flowing “upstream” (against the net electron current).

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agreement between experimental and modeled data, for the case of optically injected spins flowing to the right, and precessing due to the presence of off-diagonal strain. This strain, arising from applied uniaxial stress, causes spin precession due to a spin-orbit coupling of electron spin to the off-diagonal elements of the crystalline strain tensor in GaAs.

Very recently, we have applied our experimental techniques to the study of lateral ferromagnet/semiconductor devices that provide an all-electrical means for injection of spin-polarized electrons into semiconductors⁴. These devices, grown and fabricated in the research groups of Professors Chris Palmström and Paul Crowell, at the University of Minnesota, have ferromagnetic iron (Fe) source and drain contacts at opposite ends of a 300-μm-long channel of lightly-doped n-type GaAs (see Figure 2a). Each contact is a Schottky tunnel barrier formed by an epitaxial Fe film grown on a thin layer of highly-doped n⁺:GaAs. This design permits electrons to tunnel directly from the spin-polarized Fermi surface of iron into the n:GaAs channel.

With a small (0.4 V) voltage across the device, Figure 2b shows two-dimensional images of the steady-state electron spin polarization in the GaAs channel. Electrical spin injection from the source (left) contact, and subsequent lateral spin flow in the channel, is clearly observable.

The decay length of the injected spin polarization (~50 μm) is much less than the 300 μm channel. Therefore, in this device, injected spins lose polarization long before they arrive at the drain (right) contact, and therefore the electron current flowing into the drain is nominally unpolarized. However, the right-hand side of Figure 2b reveals an appreciable spin polarization in the channel within ~10 μm of the drain. It is possible to demonstrate, through the use of applied stress to the sample substrate, that these “accumulated” electron spins become polarized by reflection from the ferromagnetic drain contact, and that they are actually flowing upstream, against the net electron current⁴.

Moreover, these Fe/GaAs tunnel barrier contacts also function as electrical spin detectors (in addition to acting as spin injectors). Figure 3 shows the experiment. Optically-injected spin polarized electrons are caused to flow through the drain contact, and an in-plane magnetic field (B_y) forces precession of these spins parallel or antiparallel to the magnetization **M** of the drain.

The conductance of the device is larger (smaller) when the spin current at the drain is polarized parallel (antiparallel) to **M**, thereby confirming that the electrical conductance is spin-sensitive. All the essential elements of a spin transport device (electrical spin injection, manipulation, and detection) are therefore demonstrated in these structures, an important step towards all-electrical functional spin transport devices.

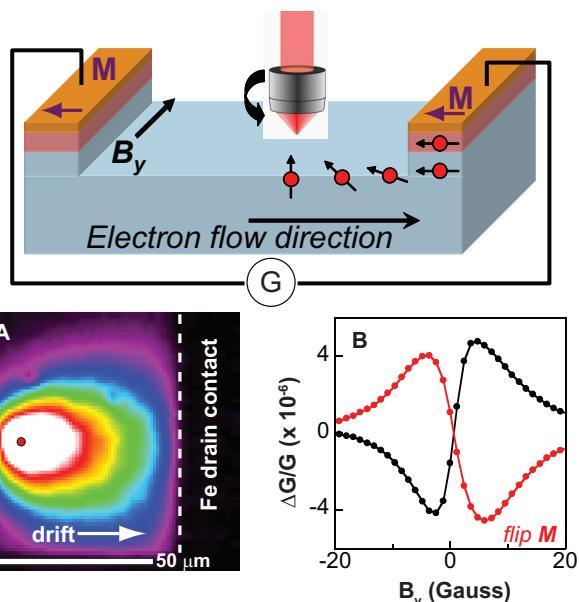


Figure 3. Spin-polarized electrons are optically injected and then transported through the ferromagnetic drain contact. An in-plane magnetic field B_y forces these spins to precess parallel or antiparallel to the drain magnetization **M**. A) A two-dimensional image of optically injected, spin polarized electrons flowing to the drain contact. B) The normalized conductivity change of the device ($\Delta G/G$) is larger (smaller) when the spin current at the drain is polarized parallel (antiparallel) to the drain magnetization **M**. The data invert when the contact magnetization is reversed (red curve), as expected.

References

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